

**TECHNICAL AND REGULATORY ASPECTS OF A
KA-BAND PHASED ARRAY ANTENNA FOR
SPACECRAFT DATA LINK APPLICATIONS**

Kenneth Perko

Code 737.2, NASA/Goddard Space Flight Center
Greenbelt, MD 20771 USA

Tel: +1-301-286-6375; Fax: +1-301-286-1750; E-mail: kenneth.perko@gsfc.nasa.gov

Joseph Deskevich

Code 501, NASA/Goddard Space Flight Center
Greenbelt, MD 20771 USA

Tel: +1-301-286-8371; Fax: +1-301-286-1725; E-mail: jdeskevi@pop500.gsfc.nasa.gov

Alan Rinker

Computer Sciences Corporation
45154 Underwood Lane
Sterling, VA 20166-9514 USA

Tel: +1-703-834-5600; Fax: +1-703-834-1094; E-mail: arinker@csc.com

John E. Miller

Stanford Telecommunications, Inc.
7501 Forbes Blvd., Suite 105
Seabrook, MD 20706 USA

Tel: +1-301-464-8900; Fax: +1-301-262-2642; E-mail: jmiller@stel.gsfc.nasa.gov

1. INTRODUCTION.

The Goddard Space Flight Center, a field center of the National Aeronautics and Space Administration (NASA), is developing the technology for a Ka-band phased array antenna system to provide high capacity communication links for the transmission of science data and Earth observation data from small, low-orbiting satellites with minimal impact on the spacecraft architecture. This development is expected to promote the use of the Ka-band spectrum allocation and NASA's next generation Tracking and Data Relay Satellite System (TDRSS), TDRSS H,I,J. These next generation TDRSS satellites are scheduled for launch starting in 1999 [1]. The phased array antenna will be designed for use in either the TDRSS Space Network or the Ground Network. The Ground Network consists of a number of earth stations deployed over the surface of the Earth to communicate with user satellites, including low-orbiting satellites, when they are in view of the earth station. The TDRSS Space Network consists of several geostationary data relay satellites (DRS) to relay communications between the user satellite and a centrally located earth station. Transmissions in the TDRSS Space Network will be from the low-orbiting user satellite to a geostationary TDRSS in the 25.25-27.5 GHz band, while transmissions in the Ground Network will be in the 25.5-27.0 GHz band.

This technology development program provides concepts and technologies required for the efficient and effective support of future NASA missions in the area of communications. When compared to many past and current missions, these future spacecraft will be extremely compact, and will have limited resources available in terms of weight, space, and DC power for the communications subsystem. This departure from past designs necessitates a re-evaluation of all aspects of the mission, including the enabling space and ground systems. One part of this re-evaluation concerns the use of higher frequency band systems, such as Ka-band, that represents a major shift in NASA's space communications frequencies. This shift is brought about, in part, by the recognition of the present and anticipated regulatory and interference pressures on NASA to move to higher bands. Use of existing communications infrastructure in the Ground Network and Space Network for S-band (around 2 GHz), X-band (around 8 GHz), and Ku-band (around 13/15 GHz) will be combined with new services in Ka-band using standardized components to yield the most cost effective means to accomplish the science mission. Figure 1 illustrates the variety of communications links in the Space Network and the Ground Network which may be used.

Figure 1 shows for an example satellite, SmallSat, that the use of the Ka-band phased array antenna system would support a 10 Mbps link with TDRSS H,I,J in the Space Network, and a 600 Mbps link to an earth station in the Ground Network.

Smallsat Communications Options

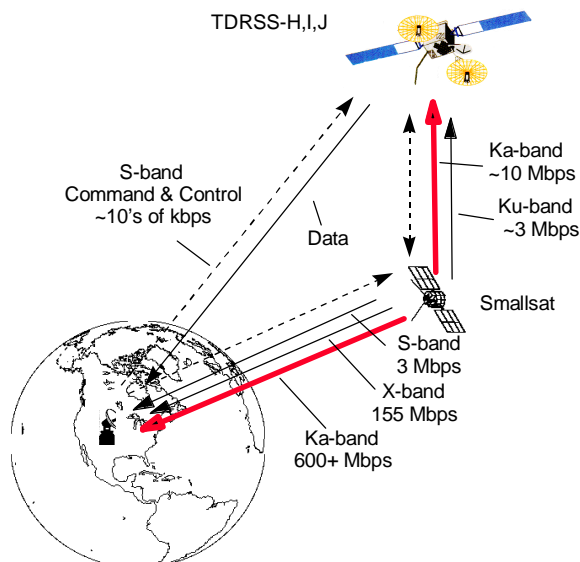


Figure 1 - Near-Earth Communications Options

Miniaturization of the spacecraft communications payload and the introduction of Ka-band operational links are the major thrusts of this program. The vision for the small spacecraft communications system is a highly integrated radio frequency subsystem that exploits recent advances in electronic devices and packaging, digital signal processing, and materials. These advances, along with new approaches to antenna design, will have a positive impact on the power, mass, volume, and cost of the communications system.

2. OVERVIEW OF THE PHASED ARRAY ANTENNA DEVELOPMENT PROGRAM.

To achieve lower costs in operating these next generation spacecraft, command and housekeeping communications will be increasingly demand-driven and asynchronous. The NASA 4th generation transponder is being developed by GSFC to satisfy these requirements, while maintaining compatibility with the existing NASA S-band infrastructure. Communications direct to Earth or via the TDRSS Space Network can be accomplished either by fixed schedule, as is currently done, or initiated independently by either the ground or the spacecraft using the future capability of TDRSS Demand Access. Small, low-cost, omni-directional antennas are used, with data rates varying from as low as 128 bits/second up to 3 megabits/second to existing ground stations. This technology is proposed as a standard for flight on all Earth orbiting missions, and has also been proposed for use on the New Millennium Program Earth Orbiting Missions. Figure 2 shows the improvement that can be achieved with this technology in several key performance areas compared to the transponder which is currently flown on NASA missions (Figure 3).

In addition to the relatively low-rate command and control communications described above, transfer of multi-terabit daily data streams of science data to central archives for Earth observation programs such as the Earth Observing System (EOS) will be required. It is also anticipated that the increasing number of end users, such as universities, will desire direct access to spacecraft instruments using low-cost ground stations. These operations will require peak data rates of tens to hundreds of megabits/second and must be accomplished with high-gain onboard antennas of a size dictated by the small dimensions of the new spacecraft. These size restrictions and the increasing international competition for RF spectrum will ultimately force all users to utilize current allocations more efficiently and develop the technology to use new frequencies such as Ka-band. This band is desirable in that it provides both wider frequency allocations for higher downlink rates and smaller antennas for a given gain due to its shorter RF wavelength. The 25.5-27.0 GHz segment of the band contains overlapping allocations for both space-to-space and space-to-Earth communications links.

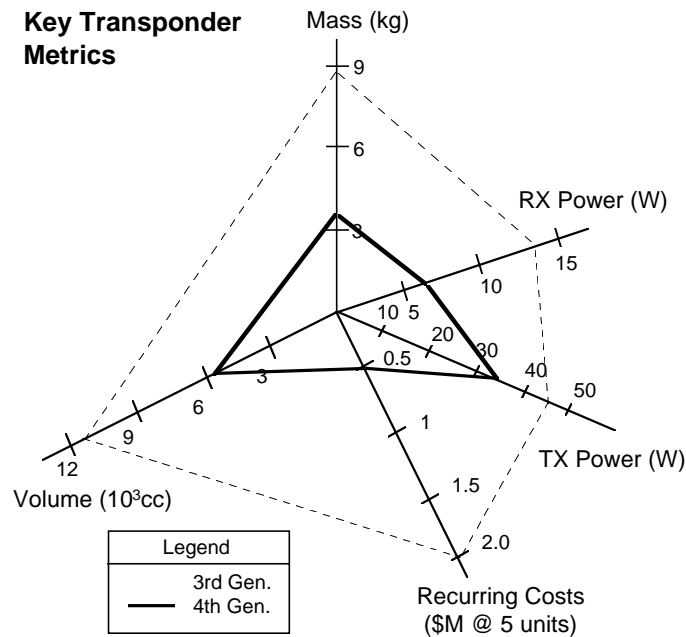


Figure 2. Expected Improvement in Performance of the NASA 4th Generation S-band Transponder
 (Values closer to the center of the chart indicate improved performance)

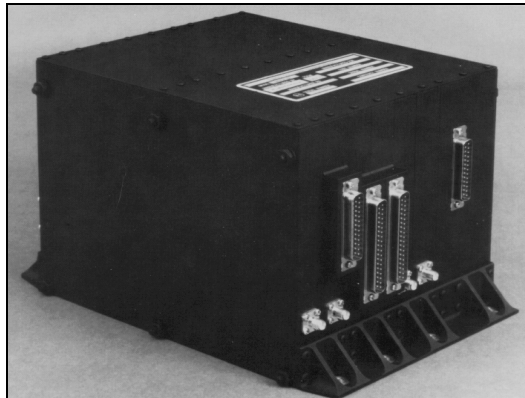


Figure 3. NASA 3rd Generation Transponder (EOS AM-1, Landsat-7)

Phased array antennas with associated high efficiency RF power amplifiers are seen as an efficient means to provide high gain for science downlinks without the deployable structures, moving parts and torque disturbances that are intrinsic to current mechanically steered high-gain antennas. Antenna concepts being developed by GSFC would operate in current international frequency allocations to enable data returns direct to Earth at very high rates for short periods (hundreds of Mbps during short 10 to 15 minute overhead passes) and via the TDRSS to the central earth station of the Space Network located at White Sands, New Mexico (approximately ten Mbps during up to several hundred minutes of contact opportunity per day). Figure 4 estimates the improvement in performance that can be achieved with a Ka-band system compared with NASA's Landsat-7 X-band system, which is typical of a direct to Earth, high rate downlink system using current technology. Figure 5 illustrates one of several potential architectures for the phased array.

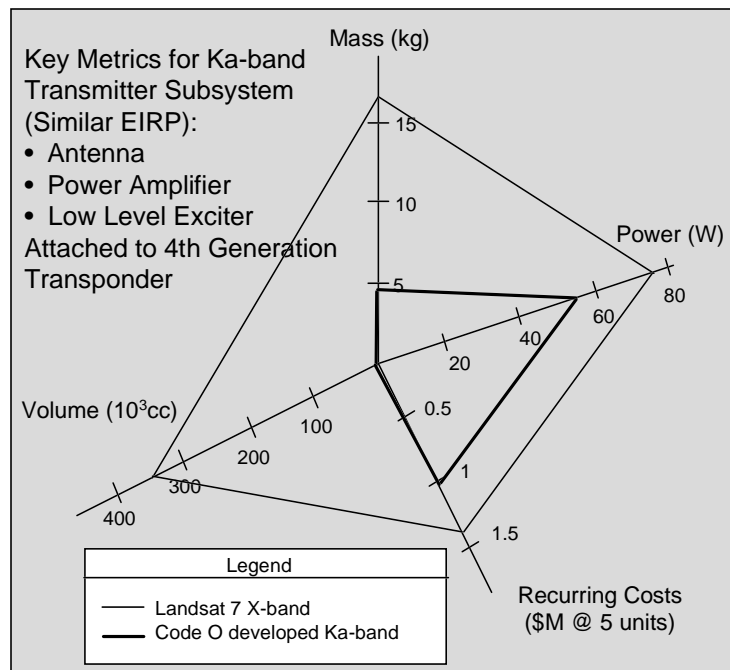


Figure 4. Expected Improvement in Characteristics of a High Data Rate Transmitter. Values for volume include the antenna gimbal for the X-band system. (Values closer to the center of the chart indicate improved performance)

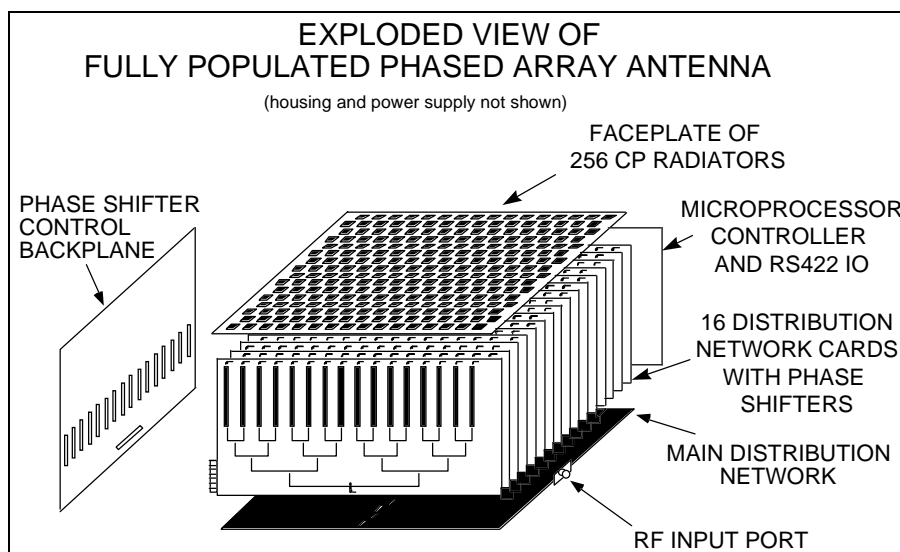


Figure 5. One of several potential phased array architectures

GSFC intends to initiate the development of a Ka-band phased array antenna before the end of 1996. This array is desired to enable high rate data returns from LEO satellites via either TDRSS or ground stations and have the basic characteristics given in Table 1.

In summary, the NASA vision of space exploration in the next decade and beyond is predicated on the development of small, low cost spacecraft. The GSFC Advanced Technology Program has been oriented toward the development and flight of new spacecraft technologies which meet this vision.

Table 1 - Basic characteristics of the phased array antenna.

Maximum Envelope Dimension	30.5 cm
Transmit Frequency (via TDRSS)	25.25-27.5 GHz
Transmit Frequency (space to Earth)	25.50-27.0 GHz
Center Frequency Channel Spacing	25 MHz
Effective Isotropic Radiated Power	33dBW minimum
Supported Data Rates (via TDRSS)	up to 10 Mbps
Supported Data Rates (space-to-Earth)	up to 300 Mbps
Modulation Scheme	BPSK / QPSK
Angular Coverage, Off-Boresight	60 degrees minimum
Polarization	LHC
Axial Ratio	3 dB
Operating D. C. Power	approx. 45 Watts
D. C. Power Source	28V +/- 5V
Operating Temperature	-10°C to 55°C
Qualification Temperature	-20°C to 65°C
Lifetime	5 years minimum

3. REGULATORY CONSIDERATIONS.

The following regulatory considerations affecting the design and operation of the phased array antenna are discussed in this section:

- Status of the allocation to enable space-to-space transmissions in the TDRSS Space Network.
- Status of the allocation to enable space-to-Earth transmissions in the Ground Network.
- Power-flux density limits.
- Reference radiation pattern.
- Spurious emissions.

3.1 ALLOCATION TO ENABLE SPACE-TO-SPACE TRANSMISSIONS.

The international Table of Allocations provides for space-to-space transmissions in the 25.25-27.5 GHz band on a primary basis in the three International Telecommunication Union (ITU) Regions. The allocation is to the inter-satellite service, and by Radio Regulation 881A its use is limited to space research and Earth exploration-satellite service applications, and also to transmissions of data originating from industrial and medical activities in space. The use of the band is shared with the fixed and mobile services on a primary basis and several other services on a secondary basis. The 27.0 - 27.5 GHz segment is also shared on a primary basis with the fixed-satellite service (Earth-to-space) in Regions 2 and 3. It is the allocation to the inter-satellite service that enables the use of the band for space-to-space transmissions in the TDRSS Space Network.

3.2 ALLOCATION TO ENABLE SPACE-TO-EARTH TRANSMISSIONS.

The 25.5-27.0 GHz band is allocated to the Earth exploration-satellite service (space-to-Earth) on a secondary basis in the three ITU Regions. The secondary status of the allocation is a significant factor affecting the use of the band for space-to-Earth transmissions. Because of the substantial investments that must be made to develop Earth observing instruments and satellite systems, a primary status must be realized before operational systems are implemented in the band.

There is a real need for EES down links near 26 GHz to provide for the direct transmission of EES sensor data to Earth. Advanced technology EES spacecraft now being planned will require wider bandwidths to download their data than can be accommodated in the 8025 - 8400 MHz band, which is currently used for this purpose. Operations in the 25.5 - 27.0 GHz band would provide greater bandwidth and increased capacity for EES data downlinks. This does not, however, obviate a continuing need for EES operations in the band 8025-8400 MHz.

Advances in sensor technology are providing higher resolution instruments which in turn require ever larger bandwidths to download their data from the spacecraft. Present data rates are in the 75-150 Mbps range (requiring up to 300 MHz of bandwidth) near 8 GHz. Bandwidths as high as 1,340 MHz are forecast for some EES sensors and cannot be accommodated in the 8 GHz band.

Table 2 provides the parameters of four representative 26 GHz EES downlink systems which are currently in the design stage. The representative systems have the following features:

- Recorded data acquisition (System A). A high data rate downlink (up to 1 Gbps) from a 705 km altitude satellite. In this system, a major data acquisition Earth station receives stored data from the EES satellite using a high-gain (55.2 dBi) antenna.

- Direct data readout (System B). A moderate data rate downlink (up to 40 Mbps) from a 705 km altitude satellite. This requires a lower-cost Earth station facility which receives real-time data collected by the satellite in the vicinity of the Earth station.
- Direct high-speed data readout (System C). A high data rate downlink (up to 1 Gbps) from a 680 km altitude satellite. Very small and low-cost Earth stations are possible by the use of a high-gain steerable spot beam on the satellite. Power control on the satellite is used to ensure compliance with existing PFD limits at the Earth's surface. The low cost Earth stations receive real-time data collected by the satellite in the vicinity of the Earth station.
- Direct data readout (Geostationary) (System D). A moderate data rate downlink (up to 15 Mbps) from a geostationary satellite. This would also utilize low-cost Earth station facilities which receive real time data.

These new applications will not be brought into service until a primary allocation is secured. Recognizing this need for a primary allocation, the 1995 World Radiocommunication Conference (WRC-95) included it as an agenda item for WRC-97 [2]. Work is currently underway in Working Party 7C of the ITU Radiocommunication Sector (ITU-R WP 7C) to prepare the technical basis for a primary allocation. The preliminary results of the ITU-R WP 7C studies on frequency sharing between EESs and other services allocated in the 25.5 - 27.0 GHz band are:

- Some constraints on EES downlinks may be necessary to protect the Inter-Satellite Service.
- Power flux-density limits on the EES emissions will be necessary to protect Fixed and Mobile systems.
- Methods of sharing between EES receiving Earth stations and Fixed and Mobile transmitters need to be investigated further, but will need to include some form of coordination.

Table 2 - Performance characteristics of 26 GHz EES down links

Frequency Band (GHz)	26			
System Example	A	B	C	D
Type of Earth Station	Recorded data acquisition	Direct data read-out	Direct High-Speed data read-out	Direct data readout (GSO)
Typical minimum elevation angle(degrees)	5.0	5.0	5.0	5.0
Satellite antenna input power (dBW)	13.0	13.0	13.0	9.0
Satellite antenna gain (dBic)	28.0	25.0	39.1	41.8
Satellite EIRP (dBW)	41.0	38.0	52.1	50.8
Free space loss (dB)	189.0	189.0	188.8	213.0
Excess path loss (dB)	6.4	6.4	6.4	7.1
Earth station antenna gain (dBic)	55.2	42.5	42.5	60.1
Antenna pointing loss (dB)	0.5	0.5	0.5	0.1
Polarization mismatch loss (dB)	0.2	0.2	0.2	0.1
Modulator and demodulator losses (dB)	2.0	2.0	2.0	1.5
Receiver reference bandwidth (MHz)	1,340.0	53.6	1,340.0	10.1
Data rate (dB Hz)	90.0	76.0	90.0	71.8
Received energy per bit (dBW/Hz), Eb	-191.9	-193.6	-193.3	-182.6
Receiver system noise temperature (K)	715.9	715.9	552.7	715.4
Thermal noise power density (dBW/Hz)	-200.1	-200.1	-201.2	-200.1
Total internal noise power density (dBW/Hz), No	-200.1	-200.1	-201.2	-200.1
Eb/No	8.2	6.5	7.9	17.4
Link bit-error ratio	10^{-6}	10^{-6}	10^{-6}	10^{-7}
Satellite data handling error ratio	$5 \cdot 10^{-7}$	-	-	-
Overall received bit-error ratio	$1.5 \cdot 10^{-6}$	10^{-6}	10^{-6}	10^{-7}

Frequency Band (GHz)	26			
System Example	A	B	C	D
Type of Earth Station	Recorded data acquisition	Direct data read-out	Direct High-Speed data read-out	Direct data readout (GSO)
Threshold Eb/No (or C/N) (dB)	3.9	3.9	3.9	10.5
Power margin (dB)	4.3	2.6	4.0	6.9

3.3 POWER-FLUX DENSITY LIMITS.

Power-flux density limits do not currently apply to the use of the 25.5-27.0 GHz band (space-to-Earth) by the EES since they operate on a secondary basis. If they cause interference, they must cease operations. However, in anticipation of WRC-97 upgrading the allocation to primary, it is reasonable to apply the same power-flux density limit to satellites in the EES as now applies to satellites that operate in the inter-satellite service. These power-flux density limits ρ as a function of elevation angle δ (in degrees) are [3]

$$\begin{aligned} \rho &= -115 && \text{dB(W/m}^2 \text{ MHz)} && 0 \leq \delta < 5^\circ \\ \rho &= -115 + 0.5 (\delta - 5) && \text{dB(W/m}^2 \text{ MHz)} && 5^\circ \leq \delta < 25^\circ \\ \rho &= -105 && \text{dB(W/m}^2 \text{ MHz)} && 25^\circ \leq \delta < 90^\circ \end{aligned}$$

3.4 REFERENCE RADIATION PATTERN.

ITU-R Study Group 7, which deals, *inter alia*, with the space science services has not developed a reference radiation pattern for satellite transmitting and receiving antennas. However, as a design guide, it is suggested that the radiation pattern conform to [4]

$$\begin{aligned} G(\phi) &= G_m - 3(\phi / \phi_b)^2 && \text{dBi} && \text{for } \phi_b \leq \phi \leq 2.58\phi_b \\ G(\phi) &= G_m - 20 && \text{dBi} && \text{for } 2.58\phi_b < \phi < 6.32\phi_b \end{aligned}$$

where:

- $G(\phi)$: gain at the angle ϕ from the main beam direction (dBi)
- G_m : maximum gain in the main lobe (dBi)
- ϕ : off-axis angle (degrees)
- ϕ_b : one-half the 3 dB beamwidth in the plane of interest (3 dB below G_m) (degrees)

Some adjustment of this reference radiation pattern may be necessary to account for coma lobes at large scan angles.

3.5 SPURIOUS EMISSIONS.

Spurious emissions have been of concern to the international community for some years. The proliferation of systems, particularly space systems, has the potential for creating an electromagnetic environment that will unacceptably degrade their performance. The concern of the international community was articulated in Recommendation 66 (WARC-92) which asked the ITU-R to study spurious emissions, particularly from space systems. In response to Recommendation 66 (WARC-92), Task Group 1/3 has been formed within the ITU to examine the limits on spurious emissions as given in Recommendation ITU-R SM.329-6 [5].

Task Group 1/3 has not completed its work. However, the work currently underway in Task Group 1/3 provides an indication of the direction that the international community is taking to establish limits on spurious emissions. Two types of limits are being considered. The first is a relative attenuation in a specific reference bandwidth of $43 + 10 \times \log_{10}(P)$ or 70 dB, whichever is less stringent, where P is the mean RF power at the input to the transmitting antenna. This is to be compared to the 30 dBc or 50 dBc given in the current version of Recommendation ITU-R SM.329-6. The second type spurious emission limit would apply in bands allocated to the radioastronomy service and to passive sensor bands. Limits being considered for these services may be found in Recommendation ITU-R RA.769 [6], for radio astronomy, and Recommendation ITU-R SA.1029 [7] for passive sensors. Power-flux density and spectral power-flux density limits to apply in those bands would probably be based on a compromise between the values given in the recommendations and practical values that may be more economically met by satellite system operators.

Within the United States of America, the National Telecommunications and Information Administration (NTIA) has established standards for radiocommunication equipment used by the Federal Government [8]. Limits on spurious emissions of space systems applicable to U.S. Government space systems **operating above 1 GHz** are given in Section 5.7.1 of the NTIA Manual [8]. **The maximum level of spurious emissions must be at least 60 dB below the maximum peak spectral power density within the necessary bandwidth of the emission.**

4. SUMMARY.

Work has been started at the NASA/GSFC to develop the technology for a phased array transmitting antenna for the next generation of compact spacecraft with limited space, weight and primary power. The antenna gain will be on the order of 28 dBc and the e.i.r.p. will be 33 dBW minimum. The phased array antenna will be able to be used to transmit data to NASA's next generation data relay satellites, TDRSS H,I,J in the Space Network, and to earth stations operating in the Ground Network. An international allocation exists that permits space-to-space transmissions in the 25.25-27.5 GHz band between stations in the Space Network. A primary international allocation to permit space-to-Earth transmissions in the 25.5-27.0 GHz band in the Earth exploration-satellite service will be sought at WRC-97. Studies to establish the technical feasibility and constraints that may be needed on such an allocation are being conducted in ITU-R Working Party 7C.

The e.i.r.p. spectral density of the emissions in the direction of the Earth will be constrained by the power-flux density limits given in the Radio Regulations. A limit of -115 dB(W/m² MHz) for elevation angles from 0 degrees to 5 degrees, linearly increasing to -105 dB(W/m² MHz) for an elevation angle of 25 degrees, and remaining constant at -105 dB(W/m² MHz) for elevation angles greater than 25 degrees currently applies to space-to-space transmissions and will likely be applied to space-to-Earth transmissions if the allocation is made by WRC-97.

It was suggested that the radiation pattern of the phased array antenna conform to the reference radiation pattern given in Recommendation ITU-R S.672 [4]. It was recognized that some adjustment to the reference radiation pattern may be necessary at large scan angles because of coma lobes.

Significant work is underway in ITU-R Task Group 1/3 to develop spurious emission limits, particularly on space systems. Special consideration will likely be given to protecting radio astronomy observations in certain bands and to passive sensors, again in certain bands. It was pointed out that the National Telecommunications and Information Administration of the United States of America imposes a 60 dB spurious emission limit on all Federal Government space systems operating above 1 GHz.

5. ACKNOWLEDGMENTS.

This paper has provided an overview of the Fiscal Year 1996 (FY96) technology development program to advance communications system capabilities in support of the small spacecraft user. This program is conducted by the GSFC Mission Operations and Data Systems Directorate and the GSFC Engineering Directorate under the sponsorship of the National Aeronautics and Space Administration (NASA) Headquarters, Office of Space Communications (Code O). For further information concerning the phased array antenna development program, please contact Kenneth L. Perko, GSFC Code 737.2, at (301) 286-6375.

REFERENCES

- [1] A.B. Comberiate, D.H. Lewis, J. Deskevich, D.J. Zillig, K.H. Chambers and W.D. Horne, "Global, High Data Rate Ka-Band Satellite Communications, NASA's Tracking and Data Relay Satellite System," presented at the First Ka Band Utilization Conference, Rome, Italy, September 1995.
- [2] "Agenda for the 1997 World Radiocommunication Conference," Resolution GT PLEN-3, Final Acts of World Radiocommunication Conference (WRC-95), Geneva, Switzerland, 17 November 1995.
- [3] Section IV, Limits of Power-Flux Density from Space Stations, Article 28, *Space Radiocommunication Services Sharing Frequency Bands with Terrestrial Radiocommunication Services Above 1 GHz*, in International Radio Regulations, International Telecommunication Union, Geneva, Switzerland, edition of 1990, revised 1994.
- [4] "Satellite Antenna Radiation Pattern for Use as a Design Objective in the Fixed-Satellite Service Employing Geostationary Satellites," Recommendation ITU-R S.672, International Telecommunication Union, Geneva, Switzerland, dated 1993.
- [5] "Spurious Emissions," Recommendation ITU-R SM.329-6, International Telecommunication Union, Geneva, Switzerland, dated 1990.
- [6] "Protection Criteria used for Radioastronomical Measurements," Recommendation ITU-R RA.769, International Telecommunication Union, Geneva, Switzerland, dated 1995.
- [7] "Interference Criteria for Satellite Passive Remote Sensing," Recommendation ITU-R SA.1029, International Telecommunication Union, Geneva, Switzerland, dated 1994.
- [8] "Manual of Regulations & Procedures for Federal Radio Frequency Management," U.S. Department of Commerce, National Telecommunications and Information Administration, September 1995 Edition.